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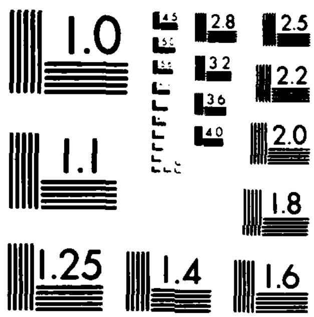

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PHYSICAL MODELING TECHNIQUES FOR MISSILE
AND OTHER
PROTECTIVE STRUCTURES

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SMALL-SCALE TESTS OF MX VERTICAL SHELTER STRUCTURES

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Abstract

The purpose of this research was to assess the applicability of geometric scaling at very small scale to study the response of buried reinforced concrete vertical shelter structures subjected to airblast loading. The approach was to build and test two 1/30-scale models and compare the responses with those from corresponding 1/6-scale tests. One of the structures tested was designed to respond elastically, and the other was designed to respond inelastically. The 1/30-scale and 1/6-scale models were built with as much geometric and material similitude as practical. Special fabrication techniques were developed for the 1/30-scale models. Concrete sand (ASTM C33) was used for the backfilled soil at both scales. The airblast from a nuclear burst was simulated with a high explosive simulation technique (HEST).

A comparison of the 1/30-scale and 1/6-scale tests shows that the surface loads and soil responses matched and that the structural responses agreed very well. For the elastic structures, concrete surface strains measured in the 1/30-scale test and reinforcing steel strains measured in the 1/6-scale test showed that the direct loading wave, the reflections from the base and the closure, the base and closure flexure, interface friction, and soil resistance to punchdown were all accurately reproduced at 1/30-scale.

For the inelastic structures, the responses agreed up to the time of failure in the 1/6-scale structure. Failure in the 1/6-scale structure occurred at an apparently locally weak section of concrete. Concrete surface strains measured in the 1/30-scale test and reinforcing steel strains measured in the 1/6-scale test showed excellent agreement above the failure location. The 1/30-scale strains throughout the structure were also in excellent agreement with the predictions of numerical analysis.

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BMO 82-003

Introduction

The major objective of this research was to assess the applicability of very small-scale modeling to the study of blast-loaded buried reinforced concrete structures. This included an assessment of the geometric and material similitude attainable for 1/30-scale models, the accuracy with which the surface loads and soil/structure interface loads could be modeled at 1/30-scale, and, of course, the fidelity of the overall structural response. The approach was to build and test two 1/30-scale models of MX vertical shelter designs and compare the responses with those from 1/6-scale tests conducted by the Civil Engineering Research Facility (CERF) at the University of New Mexico.[1] The 1/30-scale and 1/6-scale models were built with as much geometric and material similitude as practical. They were not identical to the 1/3-scale structures tested in the VST Program.[7]

The response of a vertical shelter under airblast loading is illustrated in Fig. 1. The direct load from the air blast on the structure produces flexure of the closure plate and an axial compression stress wave that propagates down the length of the structure. The airblast also produces a compressive stress wave in the soil that propagates at a lower velocity than the structure wave. This soil wave produces radial compression and vertical shear along the soil/structure interface. The magnitude of the interface shear load depends on the interface roughness and soil properties. The wave in the structure may be elastic or inelastic and may produce failure during its first passage down the tube. When the wave reaches the base of the structure, it reflects and a relief wave propagates back up the tube. The base responds in bending the shear modes and the soil beneath the base arches. This may also result in structural failure. Two or three more transits of the stress wave may occur in an elastic structure before the wave disperses and significantly attenuates. Eventually, the soil wave completely engulfs the structure, but by then surface load is nearly gone and the structure is nearly at rest.

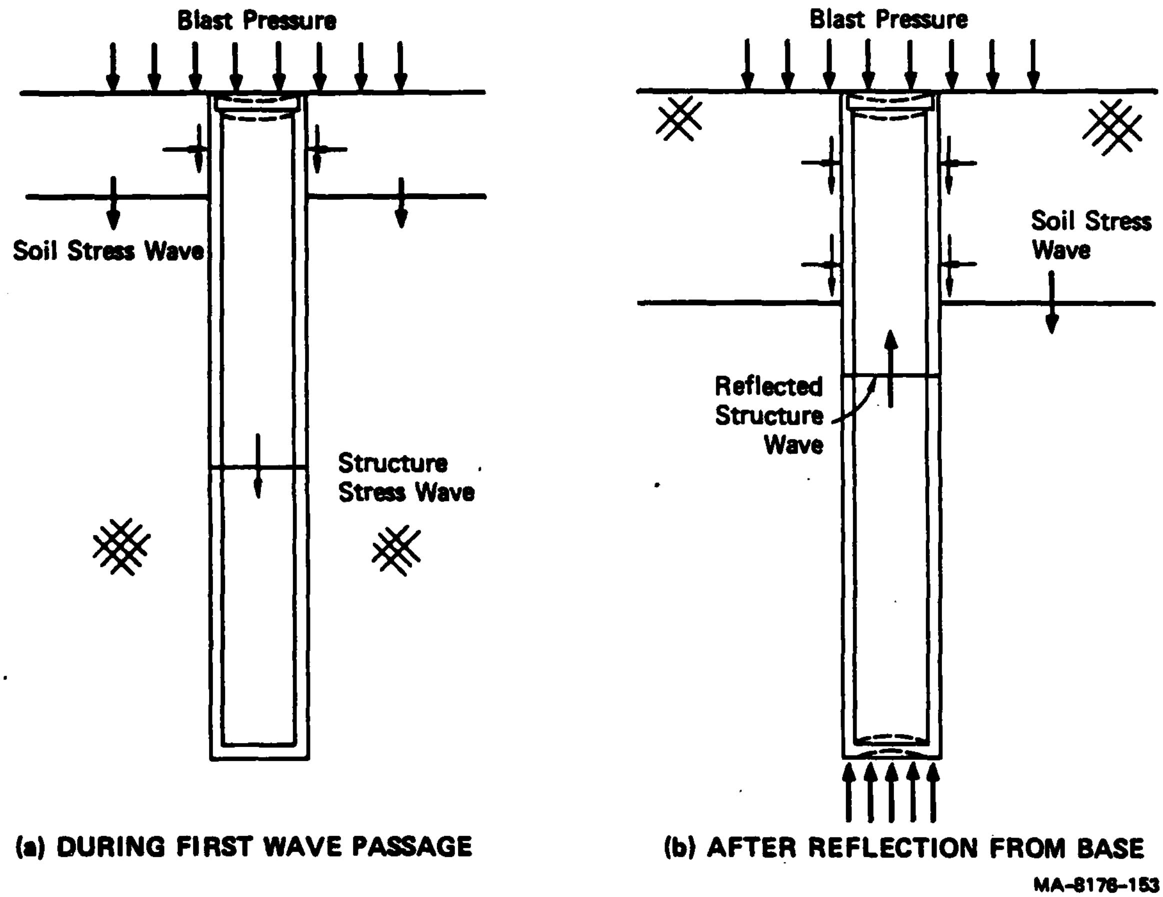

FIGURE 1 VERTICAL SHELTER RESPONSE TO AIRBLAST LOADING

Small-Scale Structural Models

The two designs that were built and tested at 1/30-scale were the 'B' structure, designed to respond elastically, and the 'A' structure, designed to respond inelastically. Geometric similitude was maintained in both the external structural dimensions and the details of the reinforcement. The overall length of the models was 1280 mm and the inside diameter was 142 mm. The wall thickness of the 'B' structure was 20 mm; for the 'A' structure it was 10 mm. Measurements showed that in both structures the walls were held to within 10% of the design thickness, except at the base where 15% variations were measured. The main reinforcement for both structures was 1% steel in the longitudinal and circumferential directions, placed in two layers. Radial stirrups at each of the approximately 4000 bar intersections provided shear reinforcement. To match the reinforcement layout of the 1/6-scale structures, wires approximately 1 mm in diameter were used in the 1/30-scale models.

The degree of material similitude achieved in the 1/30-scale models is illustrated in Fig. 2. The microconcrete used in both the 'B' and 'A' structures consisted of graded sand, water, and Portland cement, with no admixes. The strength of sample cylinders form the 'B' structure averaged 39.1 MPa with a standard deviation of 3.1 MPa. The strength of the sample cylinders form the 'A' structure averaged 23.0 MPa with a standard deviation of 2.7 MPa. In neither case was any trend apparent in the strength variation along the length of the structures. Typical stress-strain records from the 1/30-scale microconcrete are shown in Fig. 2(a), where they are compared with records from the 1/6-scale concrete.

The main reinforcement was made of steel welding wire that was deformed and heat-treated to produce the desired bond and strength properties. Tensile tests showed that uniform strength was achieved along the length of the 1.5-m-long heat-treated wires, and strength varied less than 5% from wire to wire. A typical stress-strain record is shown in Fig. 2(b), where it is compared with 1/6-scale data. A close-up photograph of the deformed wires is shown in Fig. 2(c). The results of direct pullout bond tests are shown in Fig. 2(d), where they are compared with 1/6-scale test results and prototypical bond data.

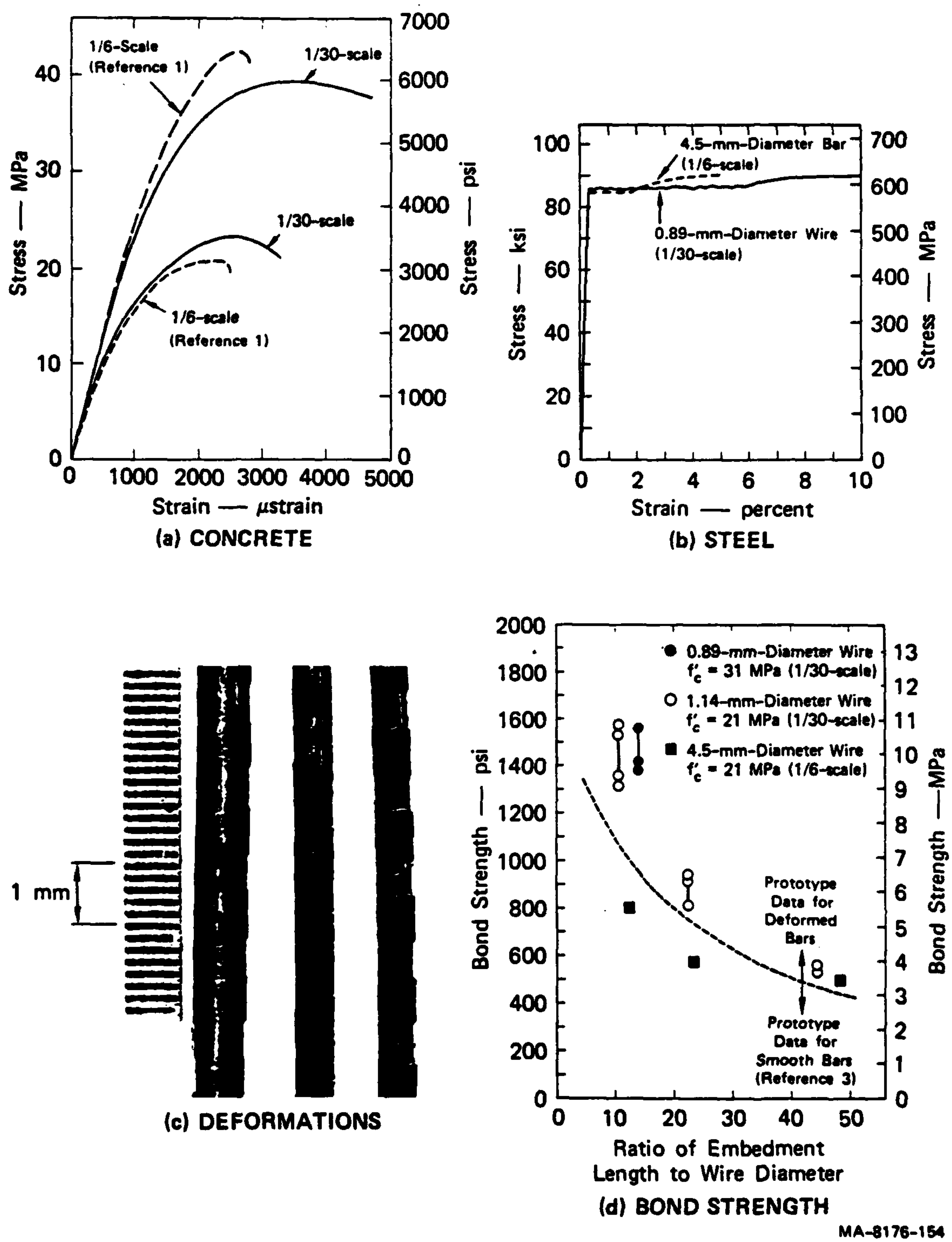

FIGURE 2 MATERIAL SIMILITUDE IN 1/30-SCALE MODELS

Test Configuration and Load Simulation

The 1/30-scale experiments were conducted in the Compact Reusable Airblast Simulator (CRABS) constructed at SRI's Corral Hollow Experimental Site. The CRABS facility, shown in Fig. 3, is geometrically similar to the Giant Reusable Airblast Simulator (GRABS) used for the 1/6-scale tests. Concrete sand (ASTM C33) was used for the backfilled soil at both scales. It was rained into place from a height exceeding 0.75 m to achieve a uniform density of about 1750 kg/m^3. The surface pressure was generated with a HEST charge.

Several types of instrumentation were used to record the loads and the structural response. A typical instrumentation layout is shown in Fig. 3. The measurements included blast pressure, vertical soil acceleration, radial and vertical soil stress, concrete strain, structural acceleration, and interface pressure. All the gage signals were conditioned and recorded in analog form, then digitized electronically at a sampling rate of 6 μs/point. In the gage records discussed below, the gage locations are given in terms of the ratio of the gage depth to the overall length of the structure (d/L). For the purpose of comparison, all the data from the 1/6-scale tests were digitized manually and scaled[2] to correspond to the 1/30-scale records.

The design load for the vertical shelter is the airblast from a 5 MT nuclear burst at the 8.3 MPa range. The Brode approximation[3] to this load was simulated at both scales using a HEST charge. The explosive charge design for the 1/30-scale tests was scaled from the 1/6-scale charge: the 1/30-scale charge consisted of four layers of Primacord explosive and polystyrene foam, covered by a 0.44-m-deep layer of sand. Direct comparisons of typical blast pressure and soil stress measurements in the structural tests are shown in Fig. 4. As indicated, the surface pressure and impulse compare very well with the design load. The soil stress measurements also compare well at both scales, although the wave speed in the 1/6-scale tests was consistently slightly higher than in the 1/30-scale tests. The cause of this difference has not been determined, but the effect on the structural response was insignificant.

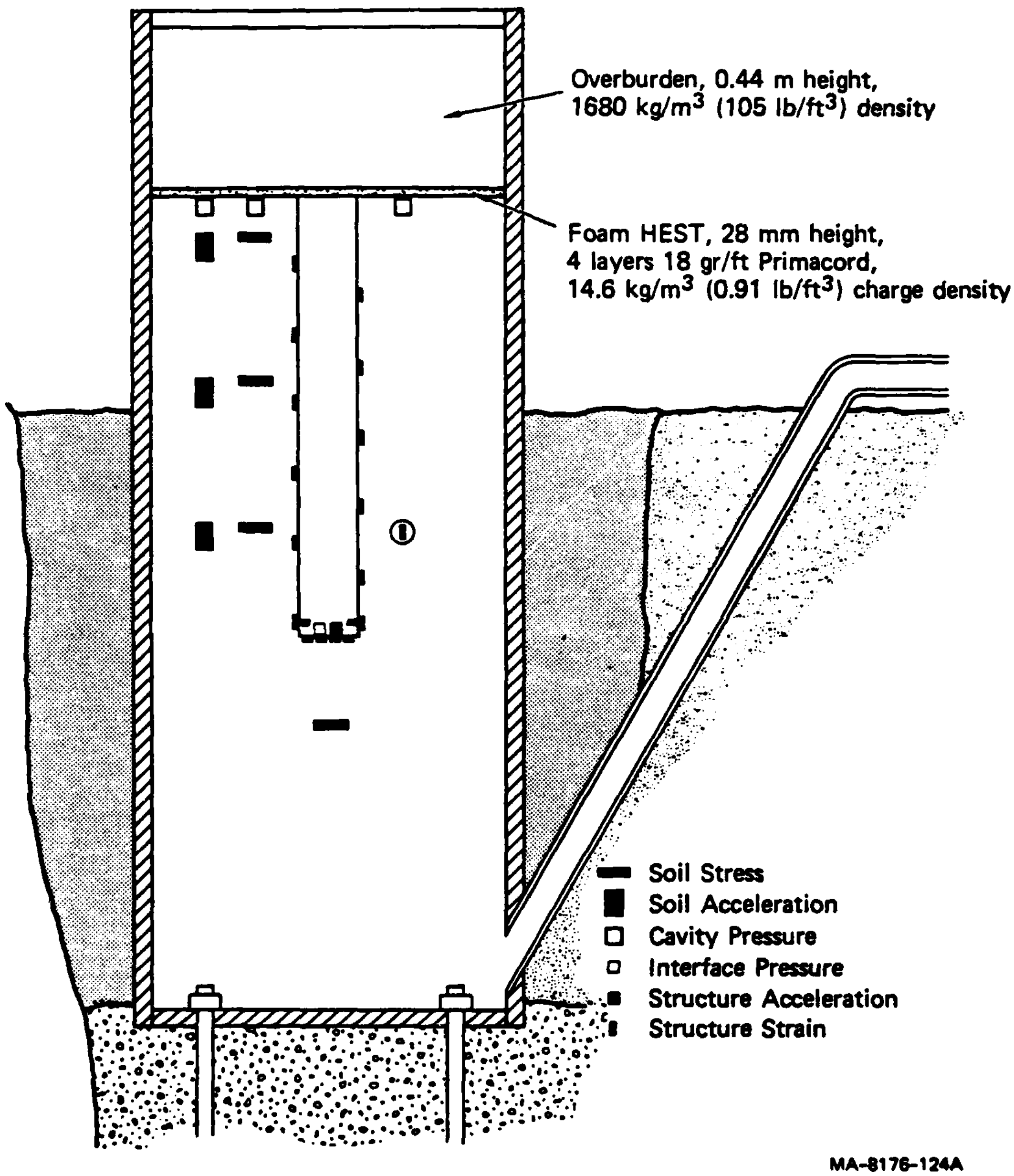

FIGURE 3 CRABS FACILITY AND TYPICAL TEST SETUP FOR 1/30-SCALE TESTS

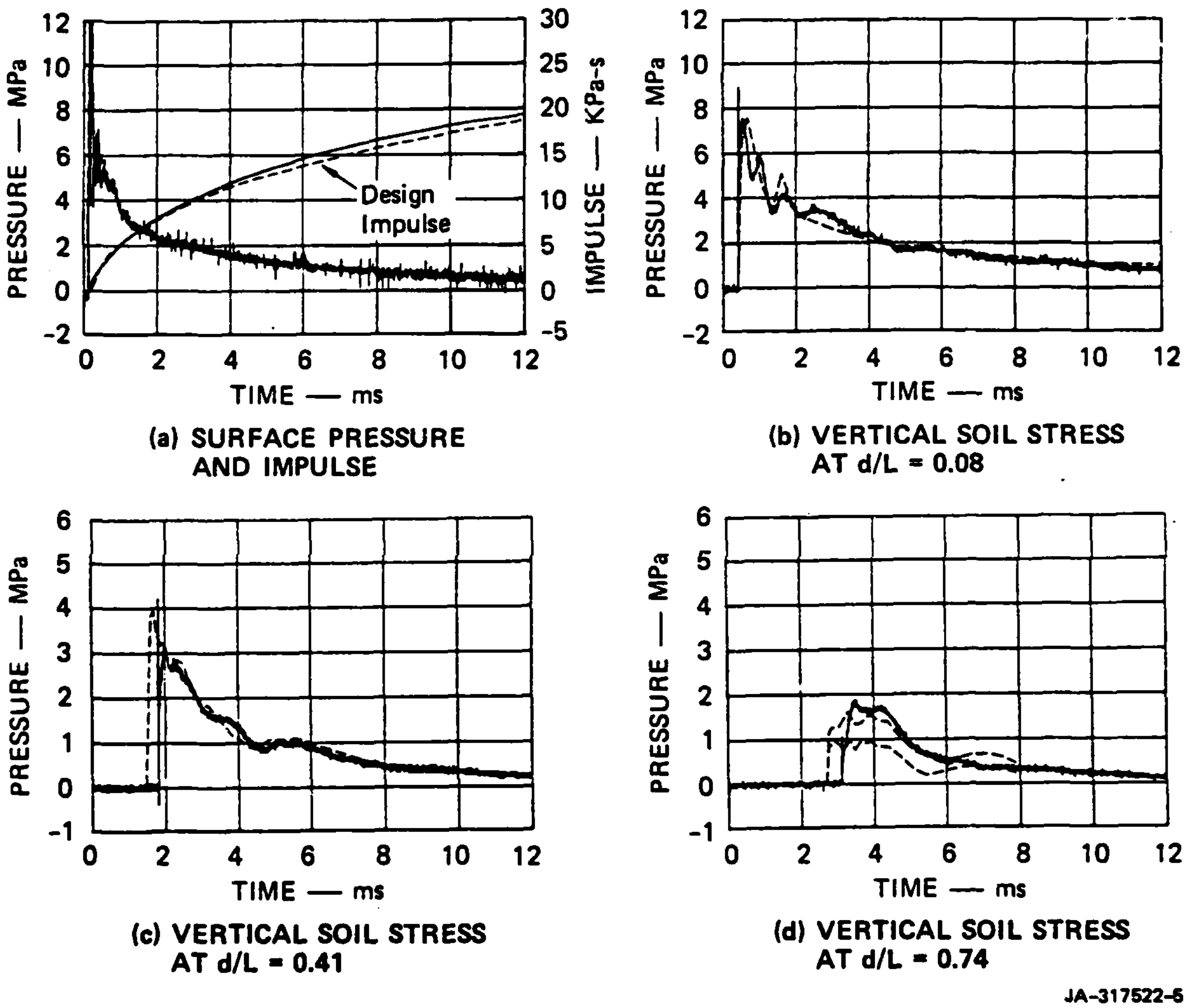

FIGURE 4 BLAST PRESSURE AND SOIL STRESSES

—— 1/30-scale; - - - 1/6-scale

Interface Shear Load Measurements

Before the structural tests, an independent set of experiments was conducted to characterize the soil/structure interface properties of the 1/30-scale models. The configuration for these tests is shown in Fig. 5. The test device was a segmented concrete column extending from the base of the CRABS facility up through the explosive cavity. The cylindrical segments were connected by load-measuring "dogbones." The surface of the concrete was representative of the 1/30-scale and 1/6-scale structures. By measuring the forces between the column segments, the acceleration of the segments, and the normal interface stress, a relation between average normal stress and average shear stress at the interface was obtained for each segment. A reasonable fit to the data from these experiments is the bilinear curve consisting of the assumed soil strength envelope (zero cohesion, 30° friction angle) and an estimated interface strength envelope (0.14 MPa cohesion, 10° fricton angle). This fit is nearly identical to the model suggested by Huck[4] for smooth concrete and sand.

'B' Structure Comparison

A comparison of the results from the 1/30-scale and 1/6-scale tests of the 'B' structure shows that the surface loads and soil responses matched and that the structural responses agreed very well. The direct loading wave, the reflection from the base, the base response, and the soil shear loading were all reproduced accurately at 1/30-scale.

Concrete surface strains measured in the 1/30-scale test and reinforcing steel strains measured in the 1/6-scale test are compared in Fig. 6. The initial small oscillations in the records are the result of electrical noise generated from the detonation of the explosive. When the direct blast load wave in the structure arrived at a particular location, the axial strain rose sharply in compression. The tensile reflection of this wave from the base then reduced the axial strain sharply. Between 0.5 ms and 1.0 ms after the initial shock arrival, depending on the location, the strain again rose because of both a second stress wave reflection (from the top) and the continually increasing soil/structure interface shear load. Not shown are the circumferential

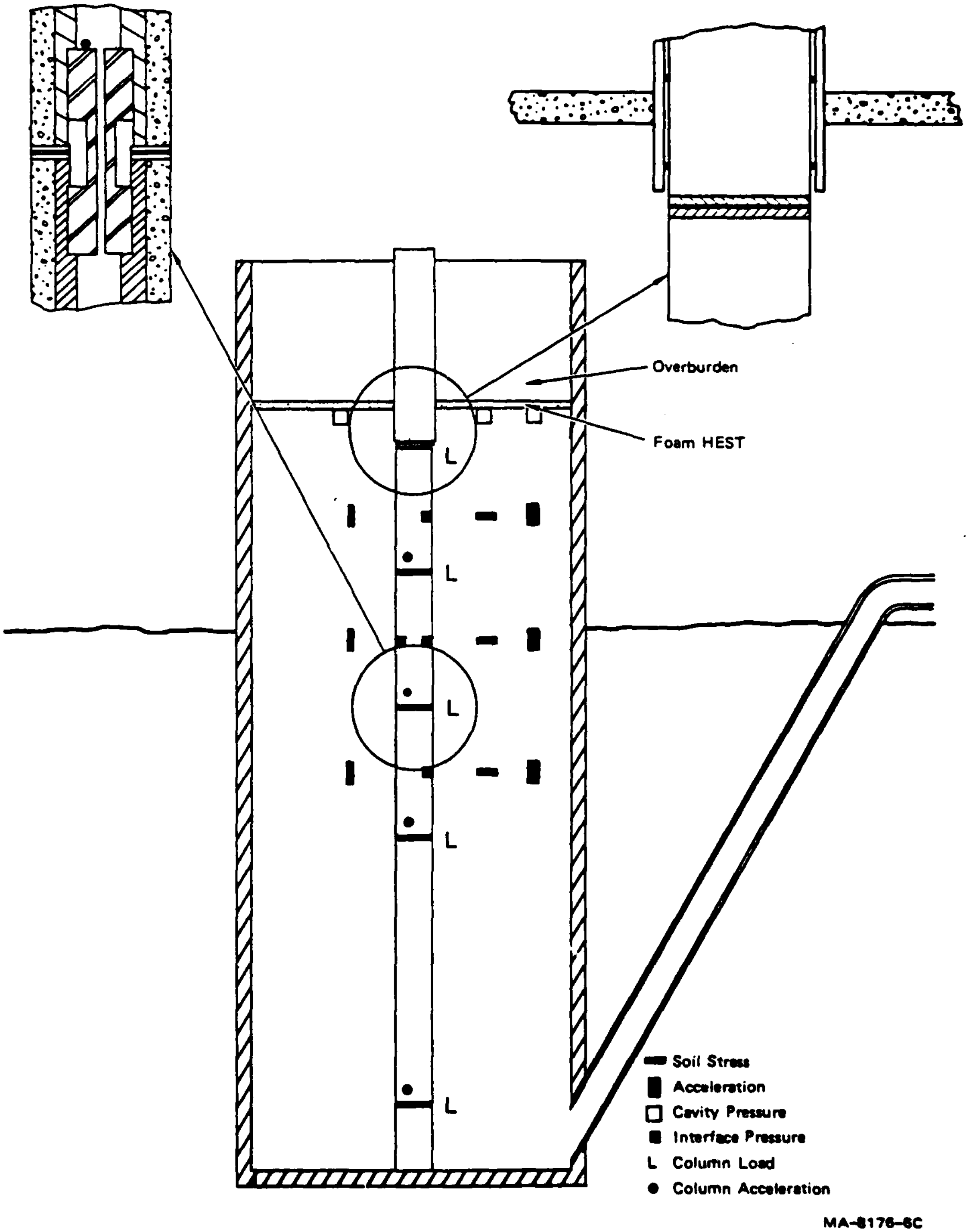

FIGURE 5 MEASUREMENT OF INTERFACE SHEAR LOADS

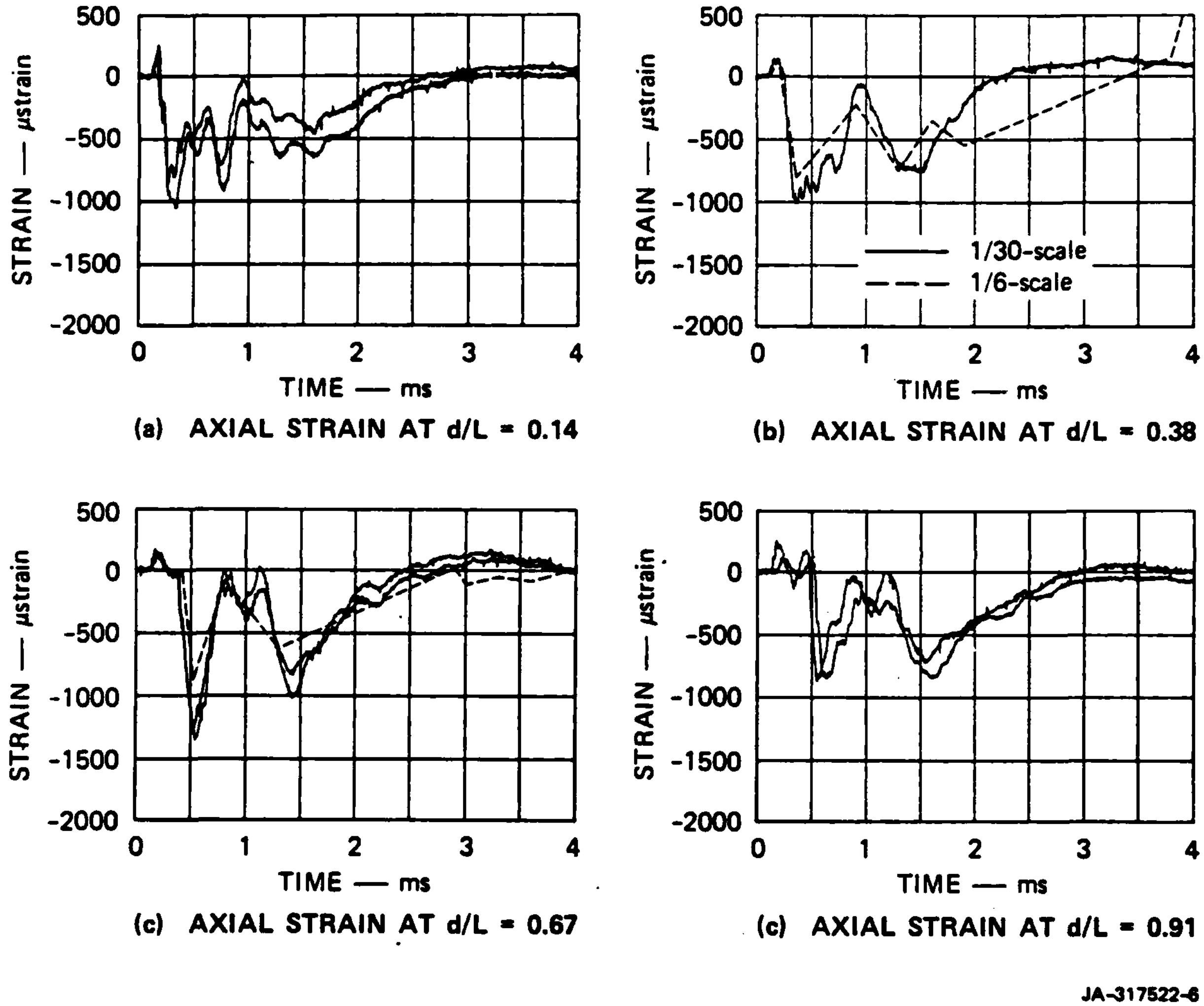

FIGURE 6 'B' STRUCTURE STRAINS

—— 1/30-scale concrete strains; ----1/6-scale steel strains

strains, which were first tensile because of the axial compression, but then fell abruptly into compression when the soil wave arrived. The comparison of the 1/30-scale records with the 1/6-scale records indicates that all the features of the response were captured in the 1/30-scale test, although the magnitude of the strains was slightly higher in the smaller model. Also, in the 1/30-scale test the peak axial compressive strain measured during the first wave transit increased with depth to about d/L = 0.67 and then decreased. Because strain was measured at only two axial locations in the 1/6-scale test, a complete comparison of the variation of peak strain along the length of the structure cannot be made.

The records showing the base response are compared in Fig. 7. Oscillations in the base acceleration and velocity indicate that flexural vibrations of the base plate occurred for about 1 ms. The difference in the magnitudes of the interface pressures from the two tests is a result of the difference in the gage locations: the 1/30-scale pressure was measured very near the center of the base, whereas the 1/6-scale pressure was measured nearer the perimeter of the base. The difference in magnitude indicates that soil arching occurred beneath the base. The soil stress measured directly below the structures, at d/L = 1.20, shows that nearly the same total load was put into the soil at both scales.

'A' Structure Comparison

A comparison of results from the 1/30-scale and 1/6-scale tests of the 'A' structure shows that the surface loads and soil response were matched and that the structural responses agreed up to the time of failure in the 1/6-scale structure. The damage in the 1/30-scale 'A' structure model is shown in Fig. 8(a). The apparent chronology is that the wave in the structure from the direct blast loading propagated all the way to the base without causing failure, and peak strains of 2200, 2000, and 2300 microstrain were recorded at d/L = 0.12, 0.38, and 0.67 locations, respectively. When the wave reached the base, or shortly thereafter, failure occurred at the tube/base junction because of a combination of axial compression, toroidal bending, and shear. In comparison, the 1/6-scale 'A' structure model, shown in Fig. 8(b), failed at d/L = 0.40 when the

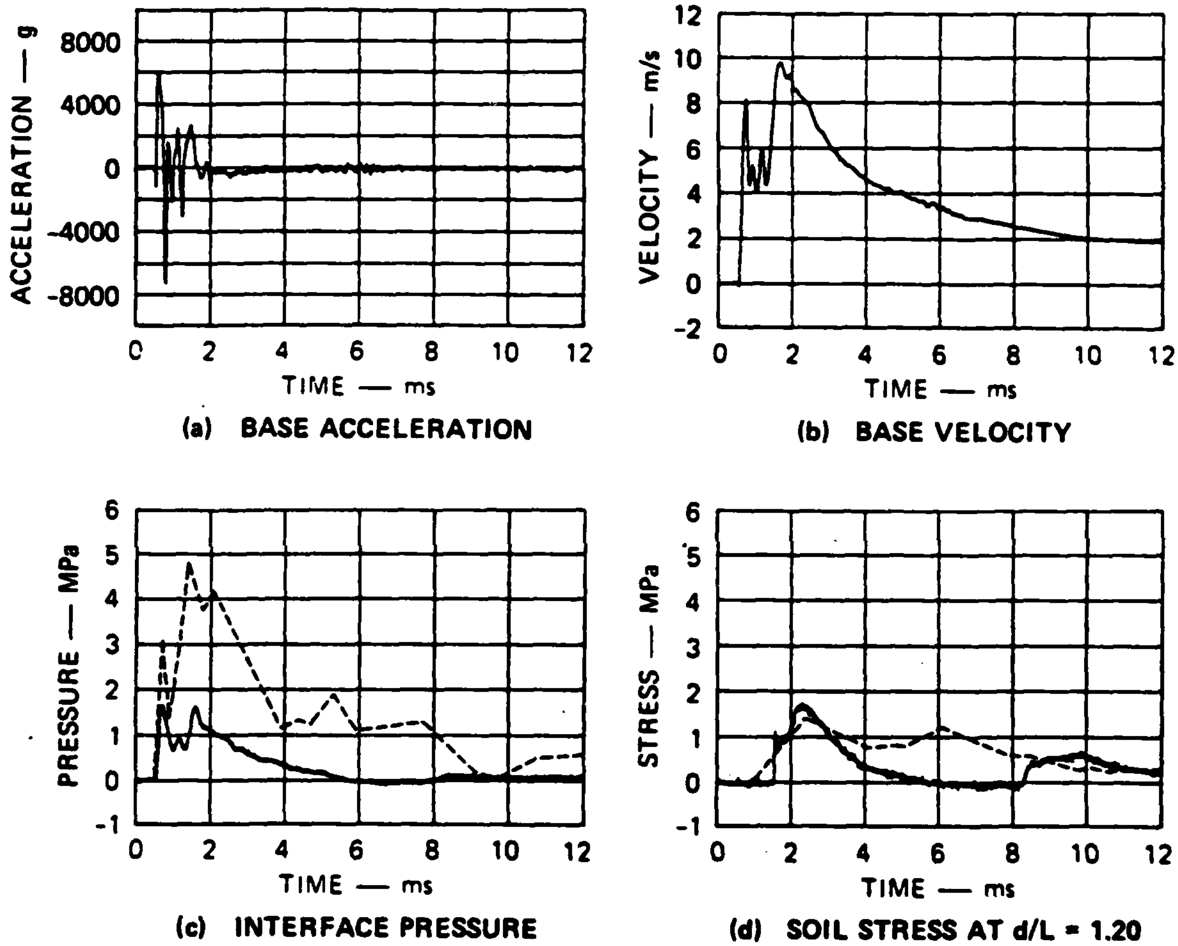

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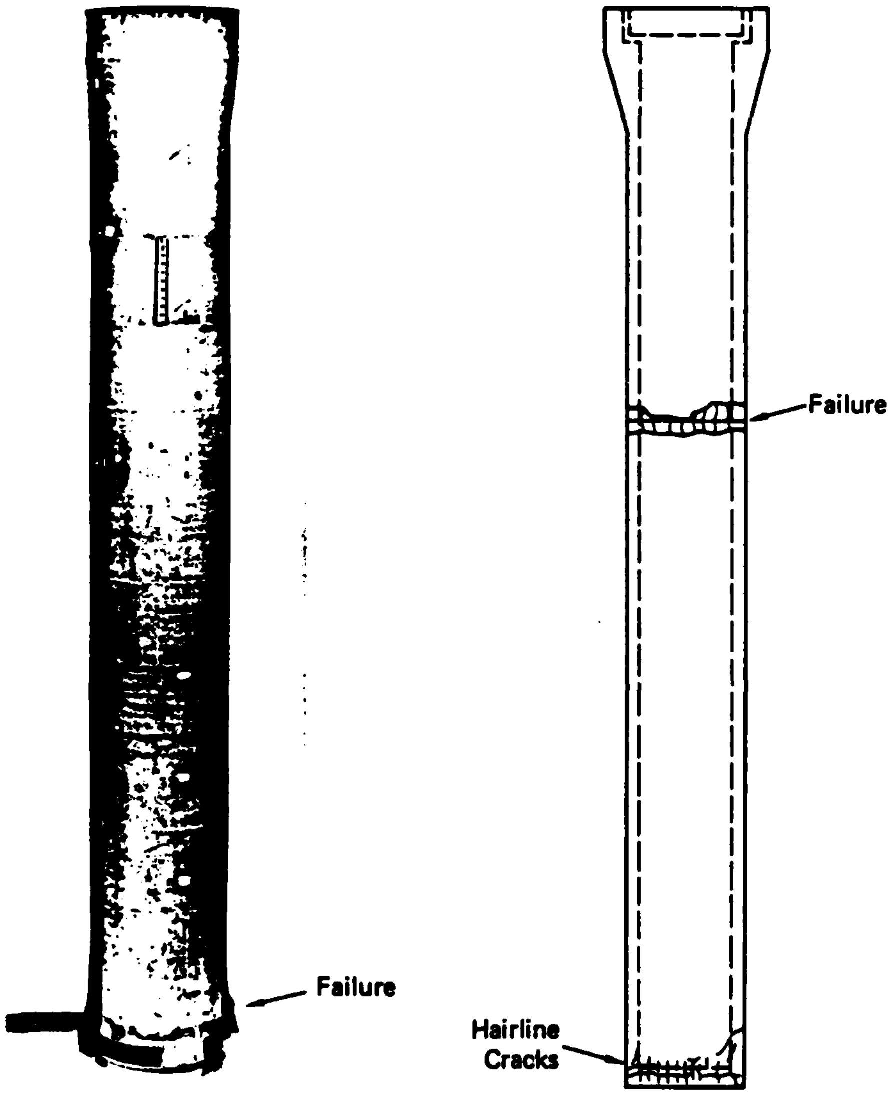
FIGURE 7 'B' STRUCTURE BASE RESPONSE
—— 1/30-scale; - - - 1/6-scale



(a) 1/30-SCALE

(b) 1/6-SCALE
(Reference 2)

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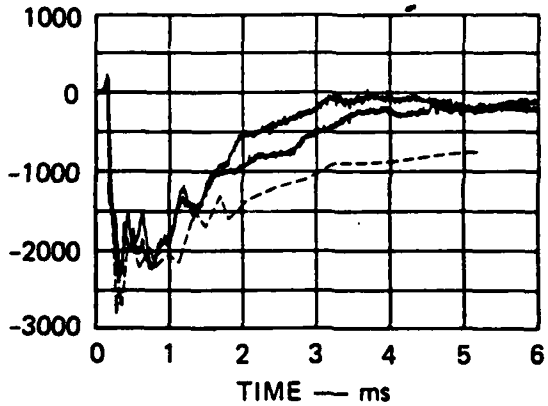
FIGURE 8 'A' STRUCTURE DAMAGE

stress wave in the structure reached that depth. The failure occurred in the vicinity of a construction joint that may have been a locally weak or brittle section. The decreased load that propagated past the failure location also damaged the base slightly.

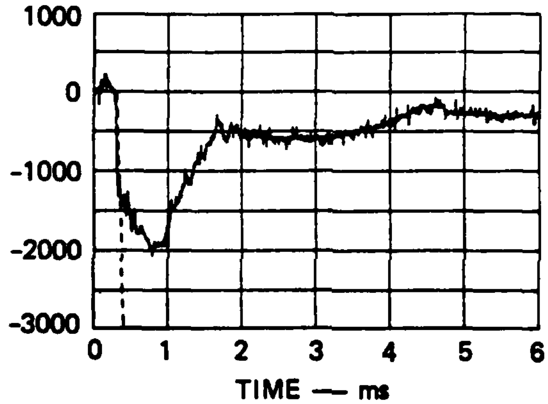
Concrete surface strains measured in the 1/30-scale test and reinforcing steel strains measured in the 1/6-scale test are shown in Fig. 9. The comparison at $d/L = 0.12$ is excellent and suggests that both structures behaved the same at very high (although different) strain rates, even though the unconfined static strength of both structures was exceeded by a factor of about 2. Because failure occurred at the $d/L = 0.40$ depth in the 1/6-scale test but not in the 1/30-scale test, the strain comparison at $d/L = 0.38$ is not good and at $d/L = 0.72$ it is meaningless.

In Fig. 10 the 1/30-scale strains from the $d/L = 0.12$, 0.38, and 0.72 locations are compared with the results of elastic-plastic finite element calculations performed by other researchers.[5,6] The agreement is good at all three locations, and neither the analyses nor the 1/30-scale experiment predict the $d/L = 0.38$-0.40 depth to be a critical location. However, during the first millisecond of response (1/30-scale) the analyses predict strains of 4000 to 5000 microstrain at about the $d/L = 0.22$ location. This is the depth at which the soil stress wave meets the reflection of the structure wave. Apparently, above that point the peak strain is limited by the radial pressure in the soil, and below that point the peak strain is limited by the relief wave from the base of the structure. Unfortunately, strain was not measured at this predicted critical location in either of the experiments because the phenomenology was not well enough understood at the time the experiments were conducted.

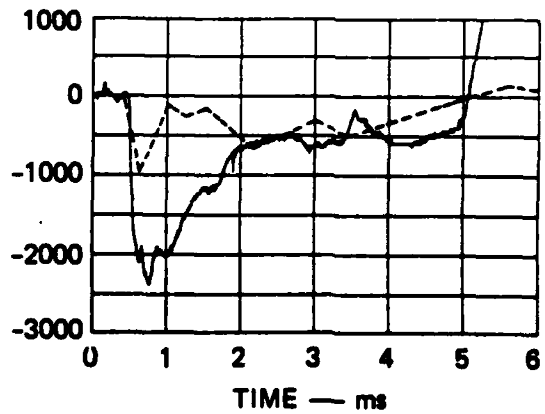
The records showing the base response are compared in Fig. 11. In contrast with the 'B' structure, significant acceleration in the 1/30-scale 'A' structure was sustained for only about 800 μs, and flexural vibration of the base plate is not evident in the velocity record. This suggests that failure took place very soon after the arrival of the direct loading wave. The 1/30-scale base damage is shown in Fig. 11(c). The soil stress measured at $d/L = 1.20$ [Fig. 11(d)] indicates that in the



(a) AXIAL STRAIN AT d/L = 0.12



(b) AXIAL STRAIN AT d/L = 0.38



(c) AXIAL STRAIN AT d/L = 0.72

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FIGURE 9 'A' STRUCTURE TUBE STRAINS

—— 1/30-scale concrete strains; ---- 1/6-scale steel strains.

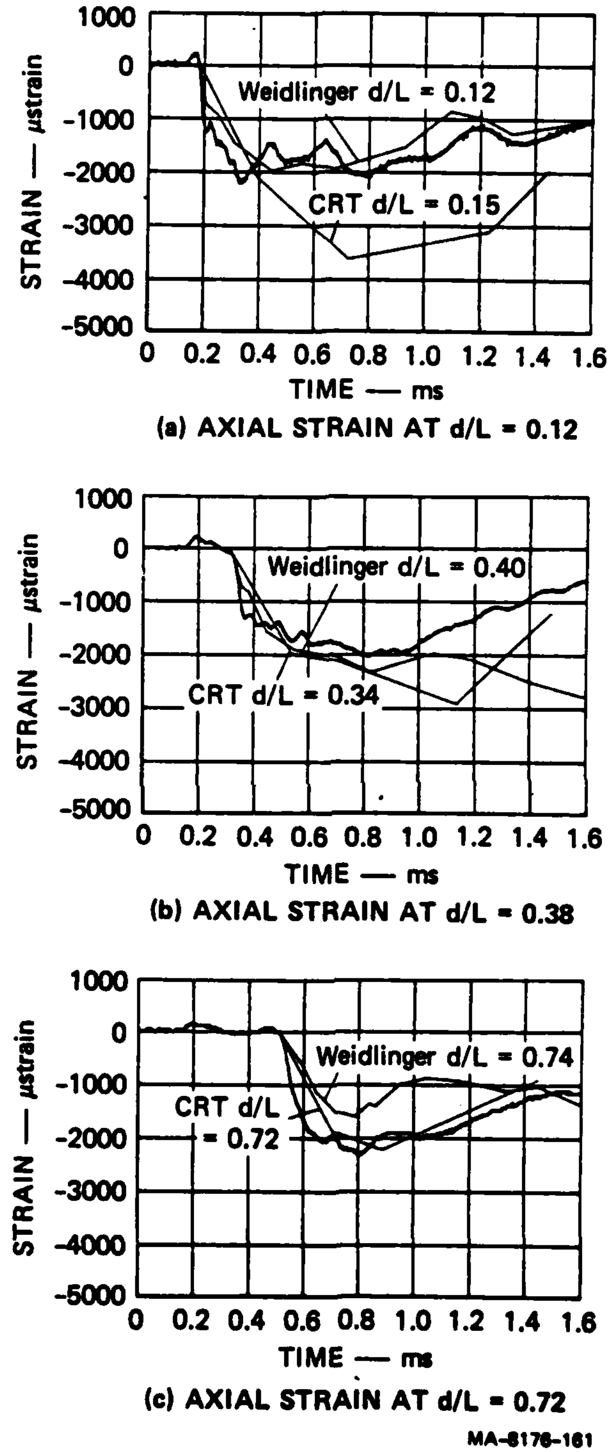
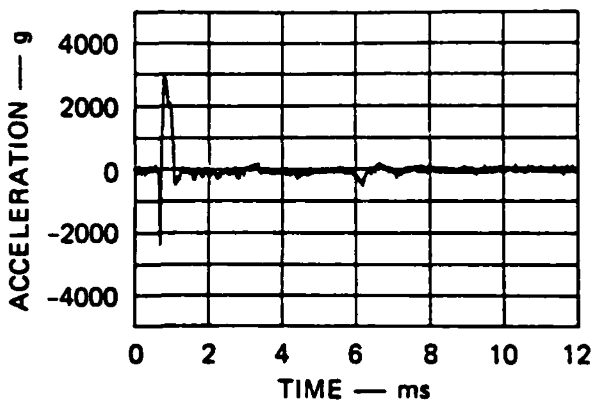
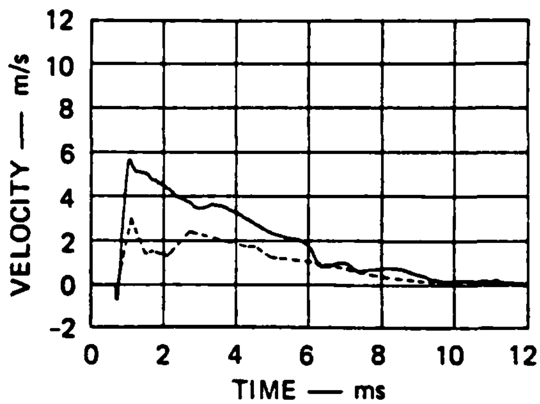


FIGURE 10 'A' STRUCTURE TUBE STRAINS COMPARED WITH ANALYTICAL PREDICTIONS

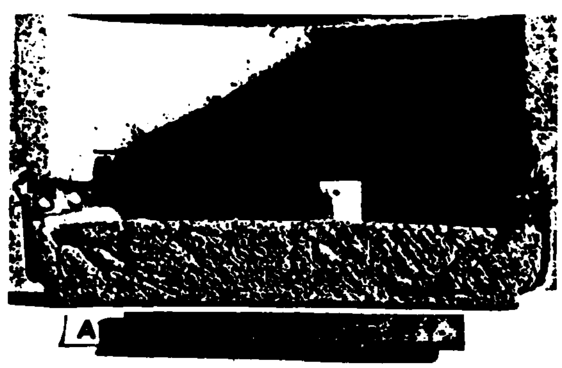
Analytical predictions are from References 6 and 7.



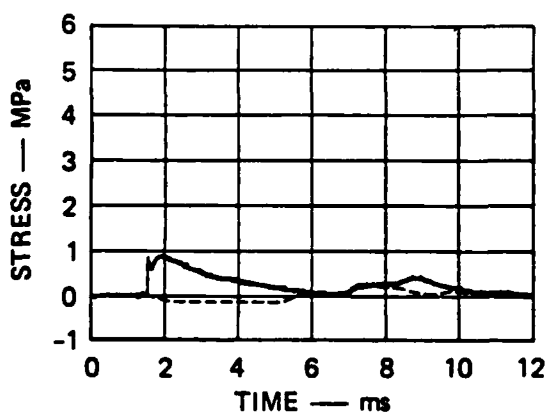
(a) BASE ACCELERATION



(b) BASE VELOCITY



(c) 1/30-SCALE BASE DAMAGE



(d) VERTICAL SOIL STRESS AT d/L = 1.20

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FIGURE 11 'A' STRUCTURE BASE RESPONSE

—— 1/30-scale; - - - - 1/6-scale

1/30-scale test a significant force was exerted by the base on the soil long after the assumed time of structural failure. In contrast, the 1/6-scale soil stress is much lower because comparatively little load propagated past the early failure at d/L = 0.40.

Analyses

Three computer calculations were conducted to aid in the understanding of the experimental results. In the first calculation, an elastic analysis of the 'A' structure was conducted to help determine the nature of the wave reflected from the base and to estimate the potential for failure at the tube/base junction. The results showed that the reflection from the base is predominantly tensile and that the principal strains at the tube/base junction are large enough to cause either compressive failure or tensile failure within 25 μs of the arrival of the wave at the base. However, because plasticity effects were not included, the actual time of the failure observed in the 1/30-scale 'A' structure test cannot be determined from this first-approximation analysis.

In the second analysis, the effect of nonscaling gravity on the early time response of a vertical shelter in cohesionless soil was studied. It was concluded that, over the range of scale factors from 1/30 to 1/3, the effect of gravity's not scaling does not cause significant differences during the transit of the first structural wave. This is the time period during which failure occurred in the 'A' structure in all three scales of the experiments.

In the third calculation, the individual effects of the direct end load and the interface shear load were investigated in a wave analysis of the 'B' structure. The comparison between this analysis and the experiments indicates that most of the experimentally observed response is caused by the direct end load, including the second rise in compression between 1.0 ms and 1.5 ms. The interface shear load has a significant effect on the magnitude of the strains at any particular time, but it has almost no effect on the shape of the strain records.

Effects of Scale

The excellent agreement between the 1/30-scale and 1/6-scale 'B' structure responses indicates that all the significant response effects that occurred in the 'B' structure tests scaled very well. These effects include elastic wave propagation and reflection in the structure, closure and base flexure, interface friction, and soil resistance to punchdown. The slight differences in the magnitude of the tube strains may be due to slight differences in concrete material properties. Gravity effects are negligible. The difference in strain rate does not produce any significant difference in response, although the variation of peak strain along the length of the structure may be a function of strain rate.

The 1/30-scale and 1/6-scale 'A' structure responses also showed excellent agreement up to the time that failure occurred in the 1/6-scale model. In particular, strains measured at the end of the transition section match very well. The only explanation for the failure in the 1/6-scale structure at the d/L = 0.40 location is the existence of a weak section. The failure location coincides with the top of a lift in the concrete formwork, where the concrete could have been weakened by the settlement of the aggregate. The excellent agreement between the 1/30-scale measurements and the computer analyses is further evidence that the smaller-scale model responded properly. Neither the 1/30-scale test nor the finite element analyses predict the d/L = 0.40 location to be critical during the first passage of the stress wave down the tube, i.e., when failure occurred in the 1/6-scale model.

After failure occurred in the 1/6-scale structure, the responses at the two scales, of course, differed. Lower strains in the tube and a lower base velocity in the 1/6-scale model resulted from the lower stress below the failed section. The higher stress wave in the 1/30-scale model produced higher strains in the lower tube and caused failure at the tube/base junction when the wave reached the base. Thus, the 1/30-scale test revealed that one weak point of the 'A' structure design is the tube/base junction. Failure at the tube/base junction isolated the base from subsequent loading through the tube, including downdrag effects. Thus, both the magnitude and the character of the base velocities differed at the two scales because of the difference in failure locations.

Unfortunately, in comparison with the 1/30-scale models and the 1/6-scale models, the 1/3-scale VST[7] models had different geometry (wall thickness variations), different material properties (higher concrete strength and lower steel strength), different loads (higher pressure), different soil (in-situ HAVE HOST), and different interface characteristics (cast-in-place roughness). Thus, it is very difficult to isolate the effects of nonscaling parameters by comparing 1/30-scale and 1/6-scale results with the 1/3-scale VST results.

For example, the strains measured in the 1/3-scale 'B' structure are about twice as high as those in the 1/6-scale and 1/30-scale structures. It appears that the combination of higher surface pressure, the cast-in-place interface condition, and the cohesion of the in-situ soil produced overall higher loads on the structure and thus higher strains. It does not appear that the differences between the 1/3-scale VST 'B' structure data and the data taken at the two smaller scales are results of scale per se.

The 1/3-scale VST 'A' structure response was similar to the 1/6-scale response in that failure occurred during the first passage of the stress wave in the structure. However, because the failure location was in the transition section, the strains before failure cannot be compared. The quicker failure in VST may have resulted from the higher load, a weak section, or the stronger interface condition.

Conclusions and Recommendations

The conclusions of this study are as follows:

(1) The geometric and material similitude in the 1/30-scale models was excellent, and the quality control was at least as good as that of the larger scale models.

(2) The blast pressure and soil structure interaction loads were accurately modeled for the conditions tested, but in-situ soil and cast-in-place interface roughness may pose modeling problems at any scale.

(3) The structural response of the 1/30-scale models was generally in excellent agreement with the 1/6-scale response. The only major discrepancy was the location of failure in the 'A' structure, and this is attributed to a locally weak section in the 1/6-scale model.

(4) The effects of nonscaling gravity were negligible for the cases studied. The effects of nonscaling strain rate were not obvious.

The tests at all three scales clearly made important contributions to the understanding of vertical shelter response. Furthermore, the response of a vertical shelter under airblast loading is dominated by those parameters that scale properly, e.g., geometry, material properties, and loads. This makes small-scale testing an excellent tool for concept screening and for verification of analytical models. However, small-scale testing should not be substituted for large-scale proof testing. Construction techniques can cause differences in response, especially as they affect strength, geometry, and interface conditions. Also, in-situ soil properties may not be accurately modeled with backfilled soil.

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